(n,γ) experiments and their implications to nuclear astrophysics

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University of Notre Dame *- Nuclear Physics Colloquium*

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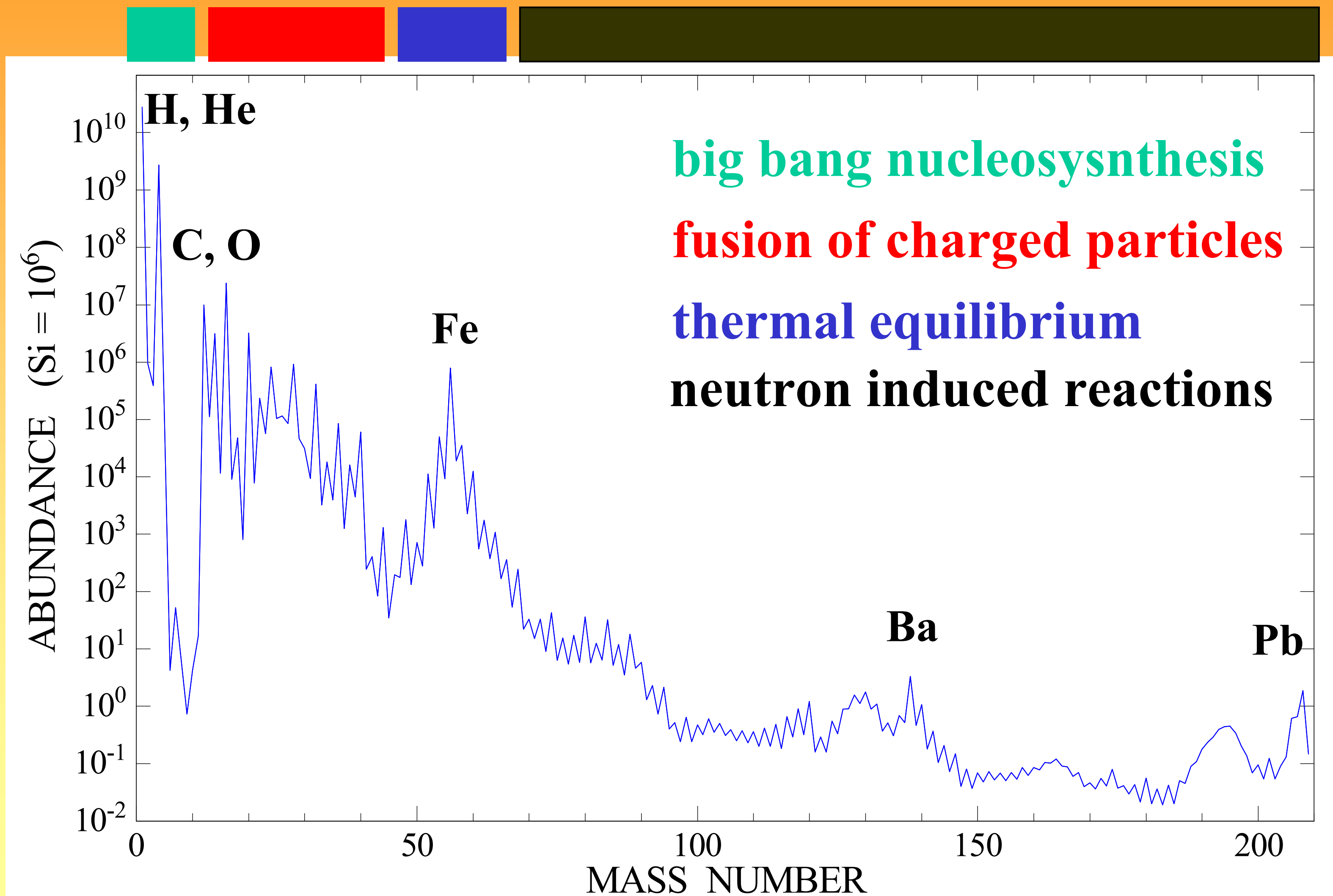
Outline

- Astrophysics – s-process
- (n,γ) experiments
  - Activation technique
  - Time Of Flight technique
- Outlook

Astrophysics

solar abundance distribution



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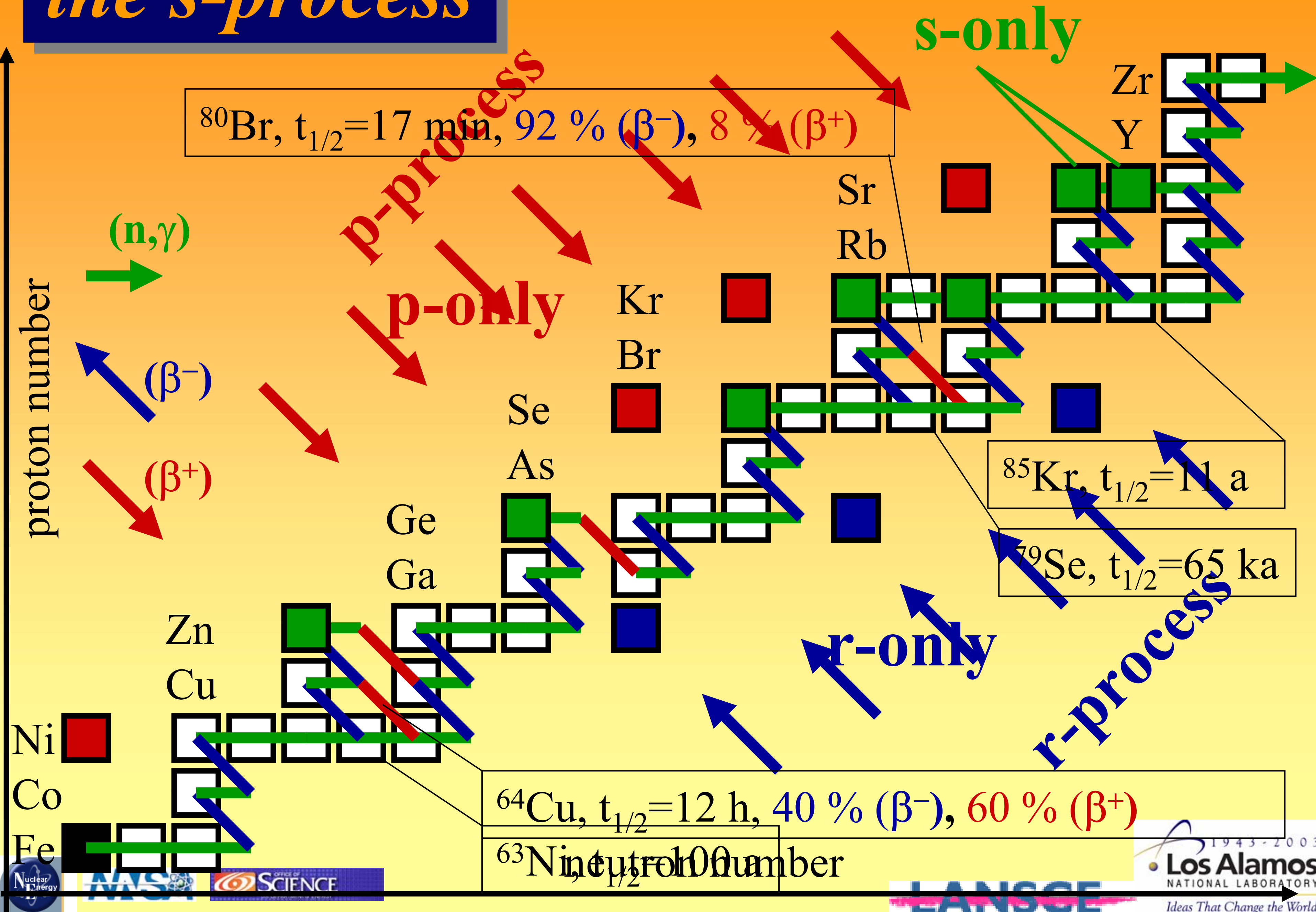
the s-process



s-process - unbranched

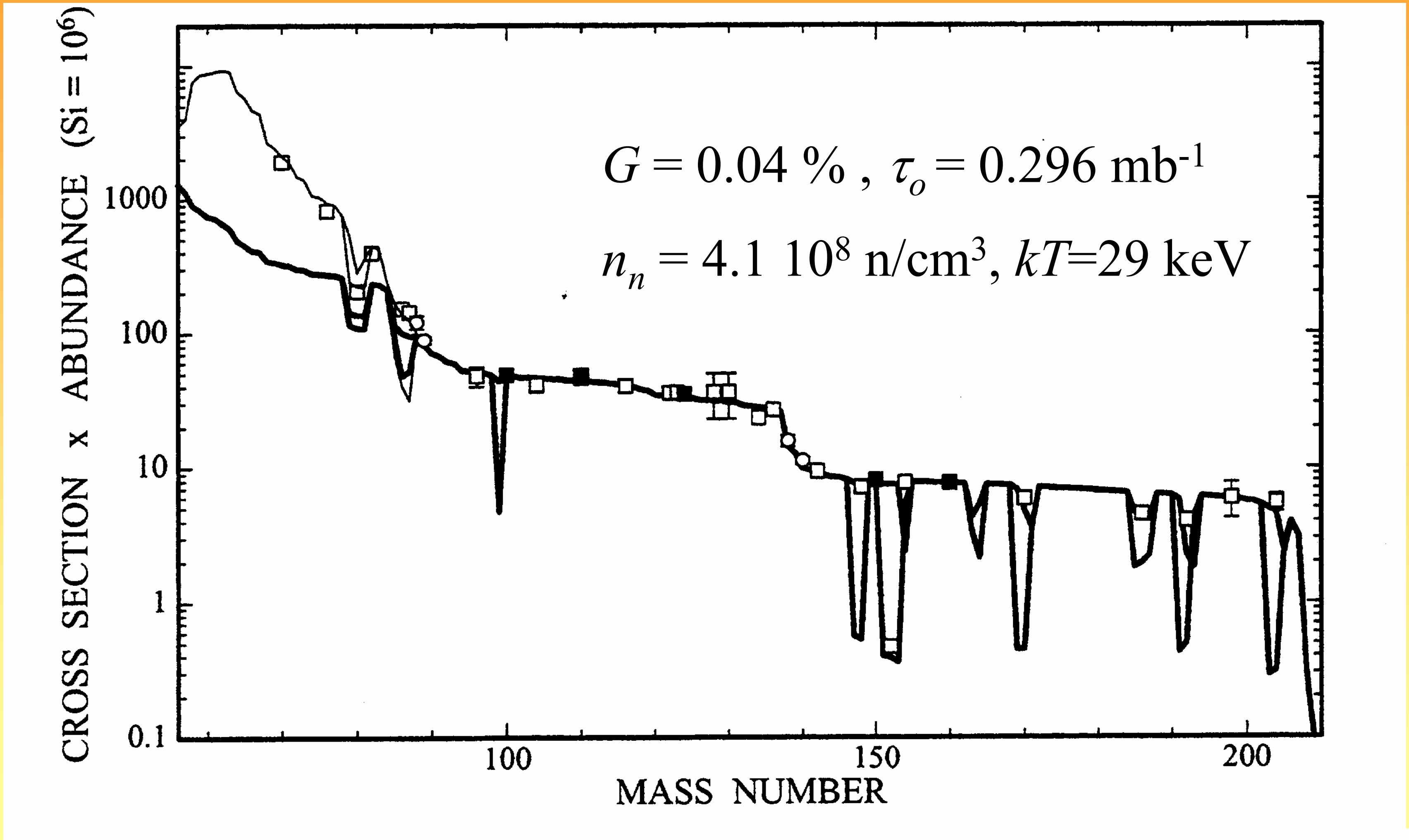
conservation of nuclei: cross section x abundance = constant

$$\left(\frac{\mathrm{d}N_A}{\mathrm{d}t}\right)^{destruction} = \left(\frac{\mathrm{d}N_{A+1}}{\mathrm{d}t}\right)^{production} \approx \left(\frac{\mathrm{d}N_{A+1}}{\mathrm{d}t}\right)^{destruction}$$

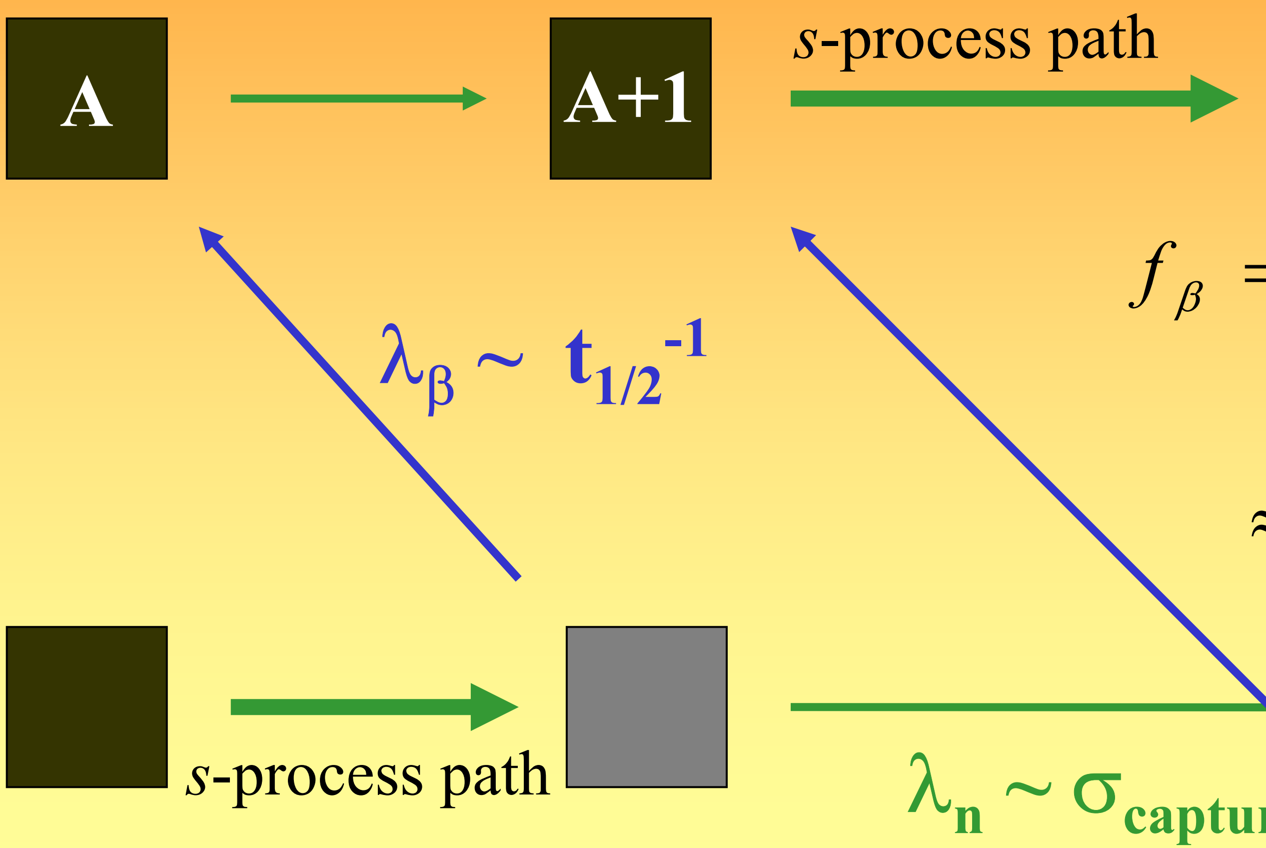
s-process path → **A** → **A+1** → *s*-process path

$$\langle \sigma_A \rangle N_A \approx \langle \sigma_{A+1} \rangle N_{A+1}$$

Nσ-systematics from the Classical Model



s-process – branched

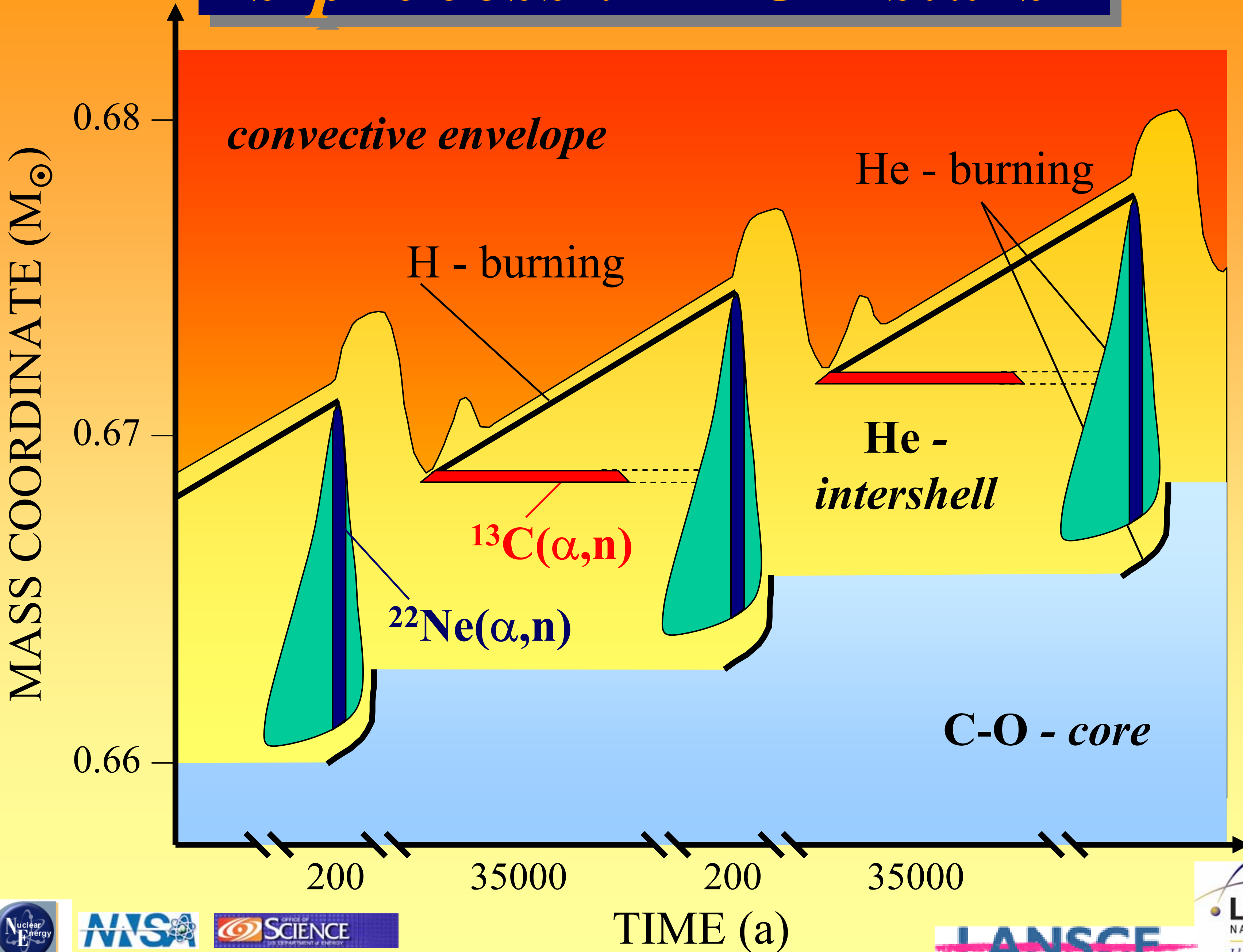


$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n}$$

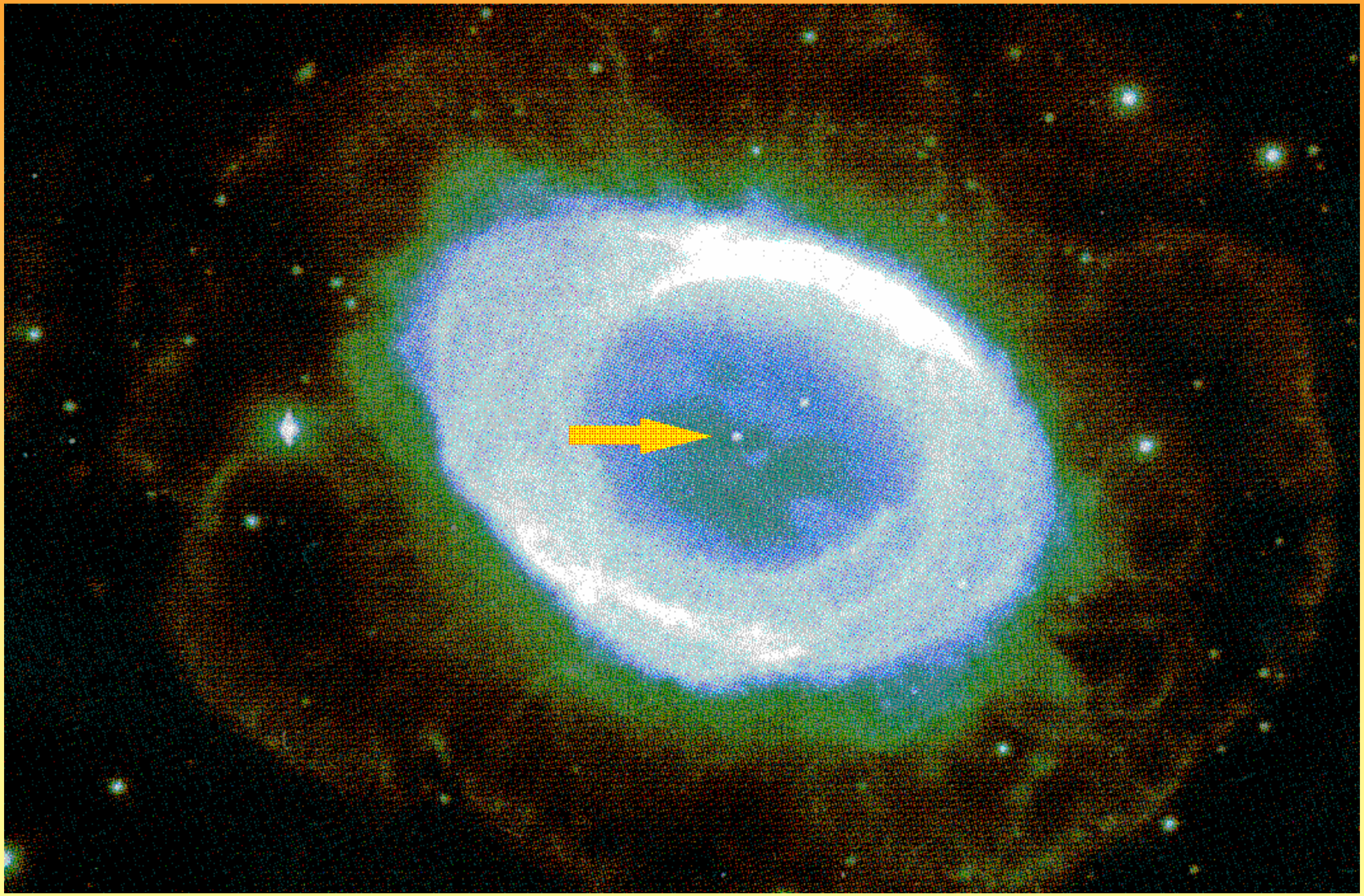
$$\approx \frac{<\sigma>_A N_A}{<\sigma>_{A+1} N_{A+1}}$$

s-process in AGB stars

Astrophysics



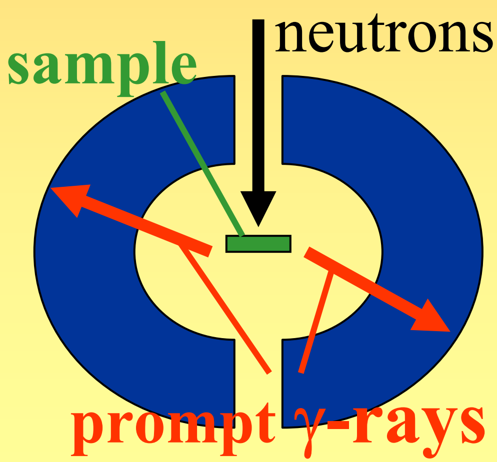
The stellar site



(n,γ) @ radiactive isotopes

PROMPT γ-detection (4π - scintillators)

- 👍 TOF experiments
- 👍 intense (white) neutron sources
- 👎 sensitivity to background



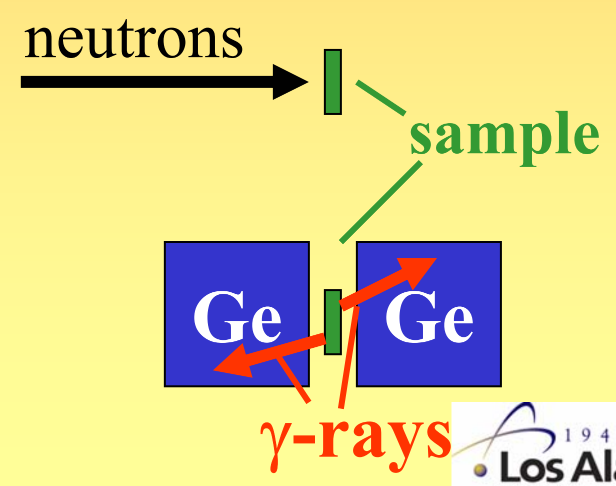
Activation technique - *DELAYED*

($^{A}X(n,\gamma)^{A+1}X(\beta^{-})^{A+1}Y$)

- 👍 very high sensitivity (~ μg)
- 👎 only average neutron energies
- 👎 only if ^{A+1}X is "reasonable" radioactive

1.

2.



Evidence for neutron capture: ACTIVATION

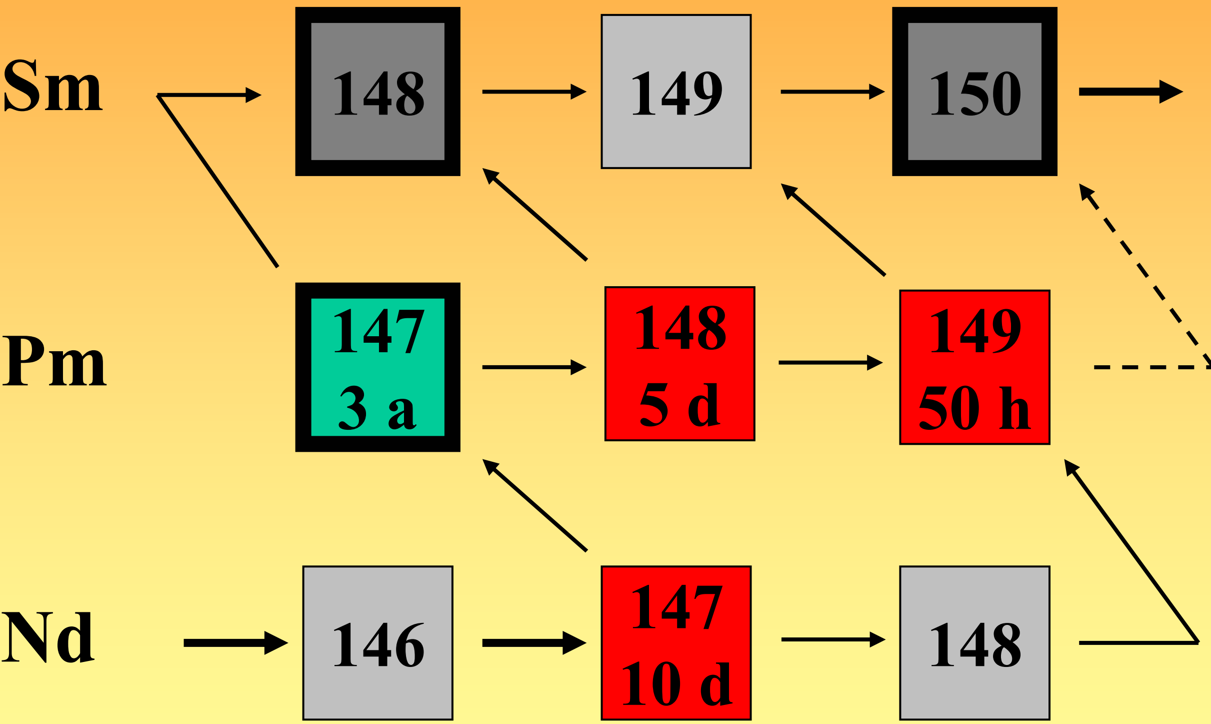
$$^{A}X + n \Rightarrow {}^{A+1}X$$

$$^{A+1}X \Rightarrow {}^{A+1}Y + \gamma + \ldots$$

Produced Activity:

$$A \propto \frac{^{A}N \cdot \Phi_n \cdot \sigma \cdot t_a}{t_{1/2}}$$

Branch point at ^{147}Pm



- 2 ***s-only*** isotopes
- ***neutron flux*** dependent
- almost independent from temperature, electron density

⇨ ***stellar neutron monitor***

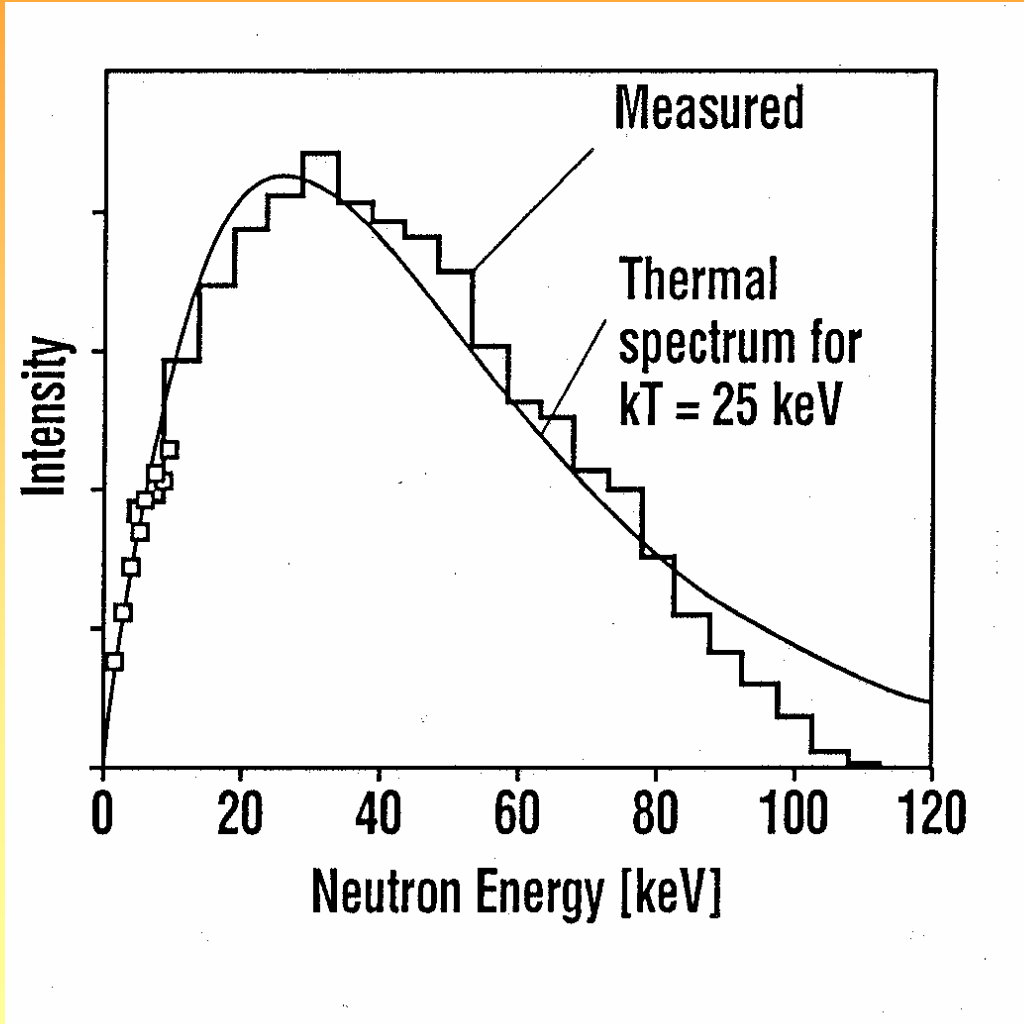
Samples

- 28 ng ^{147}**Pm** ($t_{1/2}$ = 2.6 y, 962 kBq)
- carrier: isotopically enriched ^{147}Sm
- canned in 0.3 mm graphite
- impurities: 0.0015 % ^{146}Pm ($t_{1/2}$ = 5.5 y)

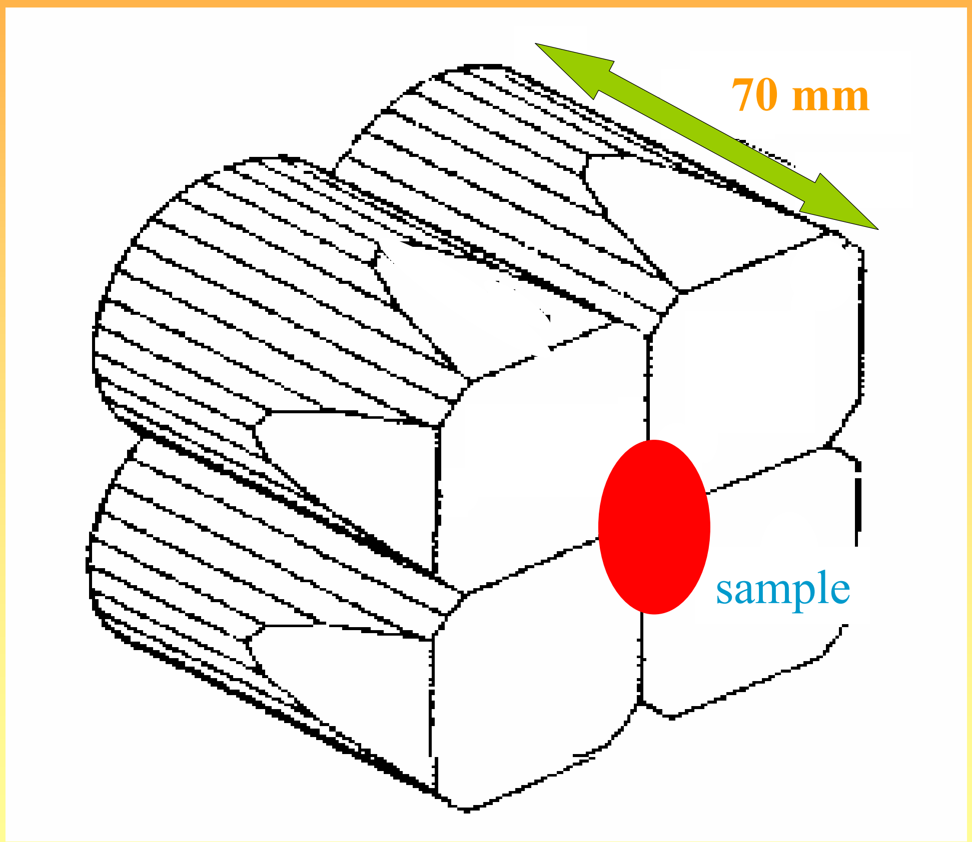
Neutron spectrum

Quasi-Maxwellian averaged distribution:

kT	=	**25 keV**
E_{max}	=	**110 keV**



γ-detection



2 Ge-Clovers, face to face

Efficiency @ 1115 keV:

single crystal:

ε_{tot} = 11 %

ε_{peak} = 1.1 %

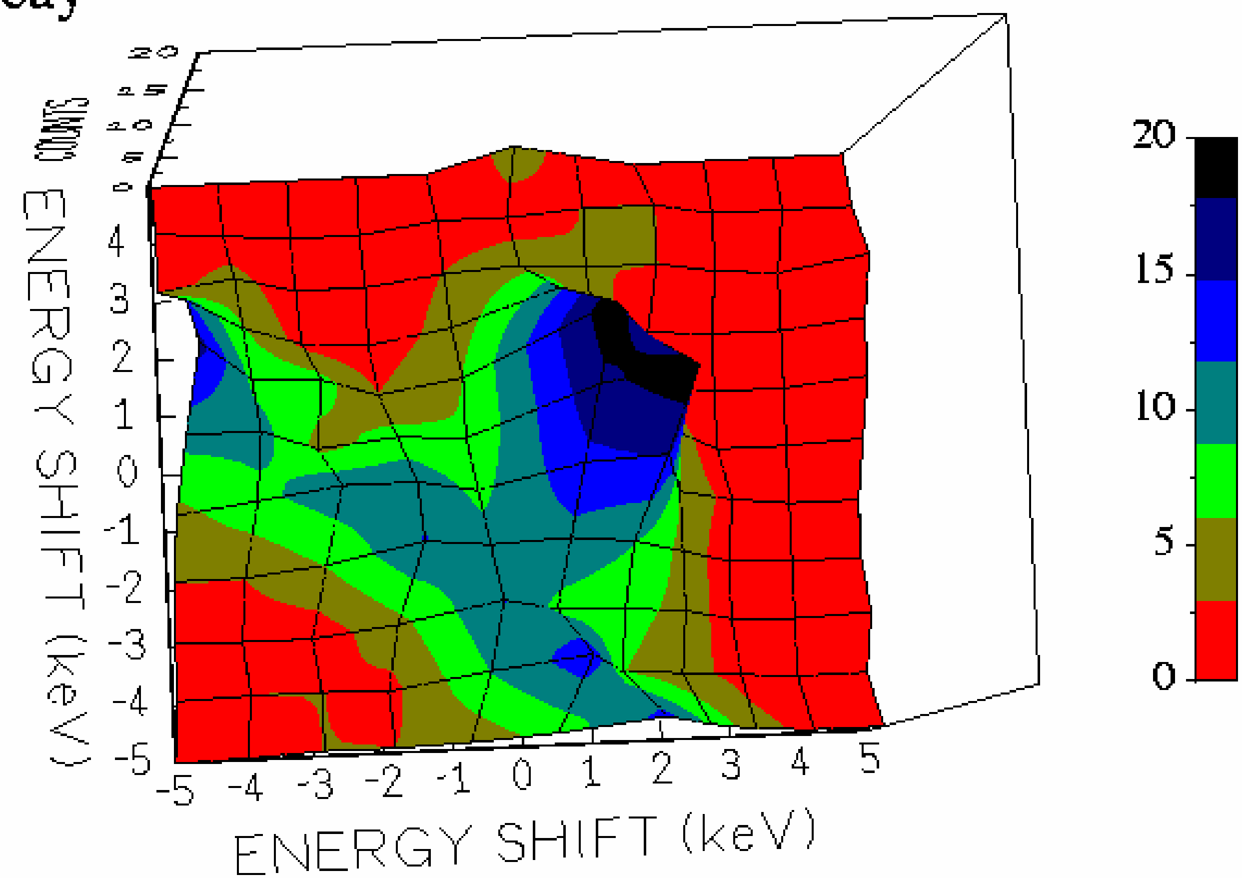
addback:

ε_{peak} = 15 %

Activation

coincidences: 550 & 915 keV

^{148g}Pm decay



Astrophysical Implications

- $N\sigma(^{148}Sm) / N\sigma(^{150}Sm)$: **0.870 ± 0.009**
- Neutron density (this exp.): **(4.94 ± 0.6) 10^8 cm^{-3}**
- Neutron density (previous): **(4.1 ± 0.6) 10^8 cm^{-3}**

Evidence for neutron capture: PROMPT

$$^{A}X + n \Rightarrow {}^{A+1}X + \mathbf{Q}$$

$$Q = \sum \gamma_i$$

⇨ **"monoenergetic" if 100 % efficiency**

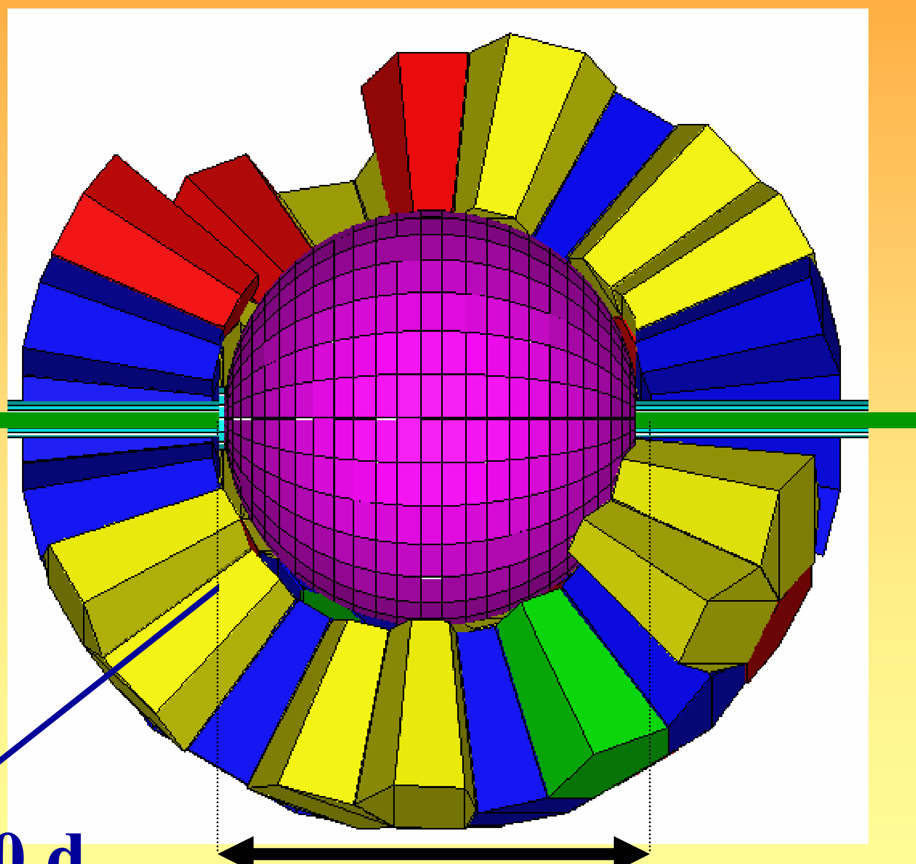
LANSCE @ LANL

TOF

TOF

Detector for Advanced Neutron Capture Experiments

collimated
neutrons
beam



sample
$t_{1/2} > 100$ d
m ~ 1 mg

34 cm

neutrons:

- spallation source
- thermal .. 500 keV
- 20 m flight path
- $3\ 10^5$ n/s/cm^2/decade

γ-Detector:

- 159 BaF_2 crystals
- 4 different shapes
- R_i=17 cm, R_a=32 cm
- 7 cm ^{6}LiH inside
- $\varepsilon_\gamma \approx$ 90 %
- $\varepsilon_{casc} \approx$ 98 %

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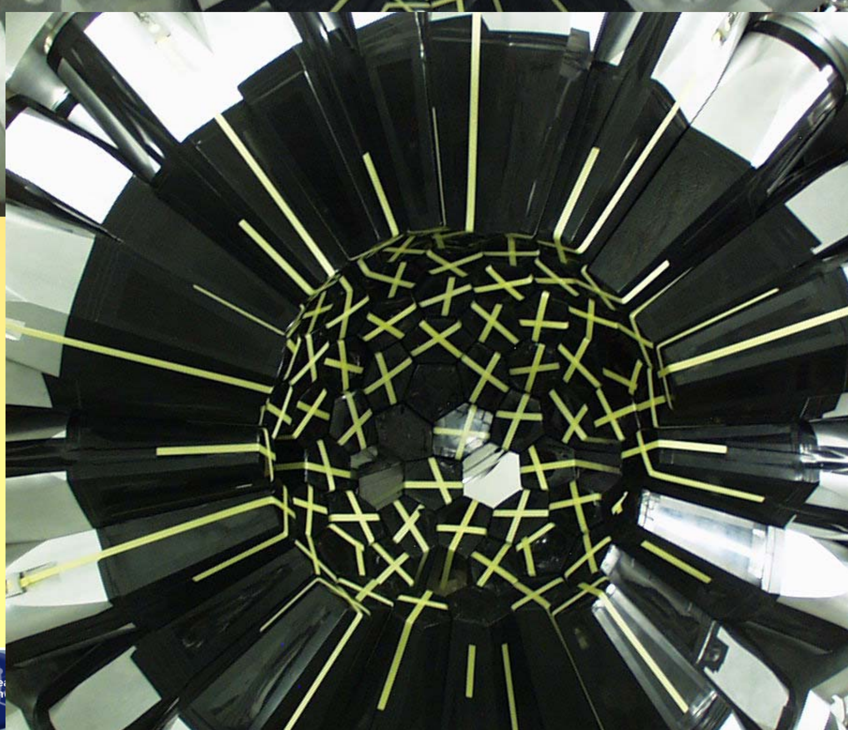
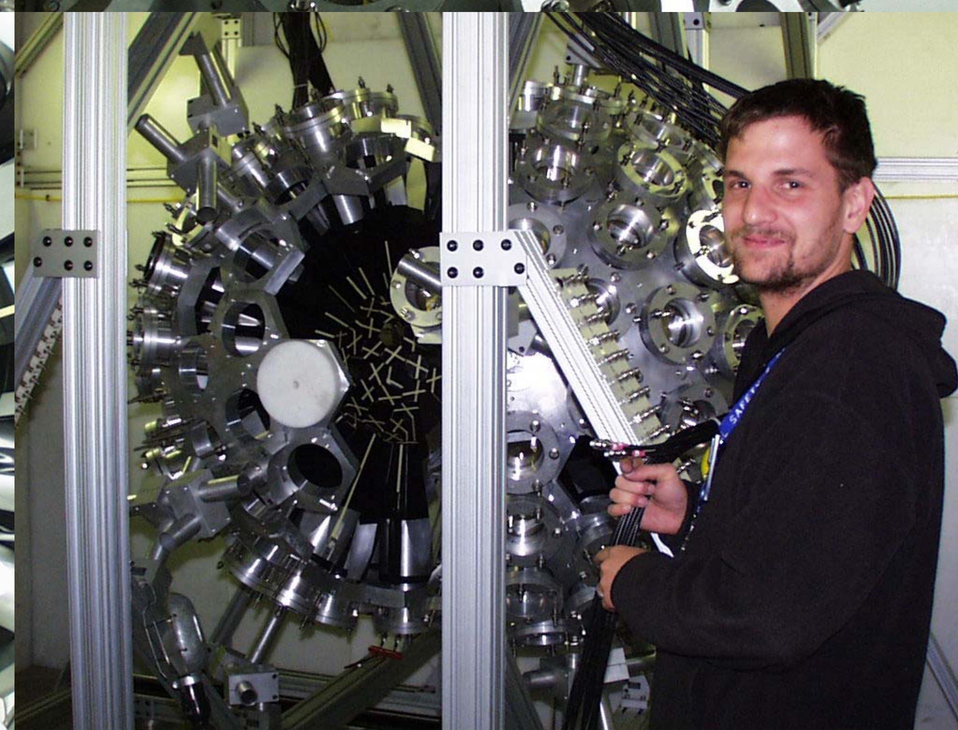
DANCE

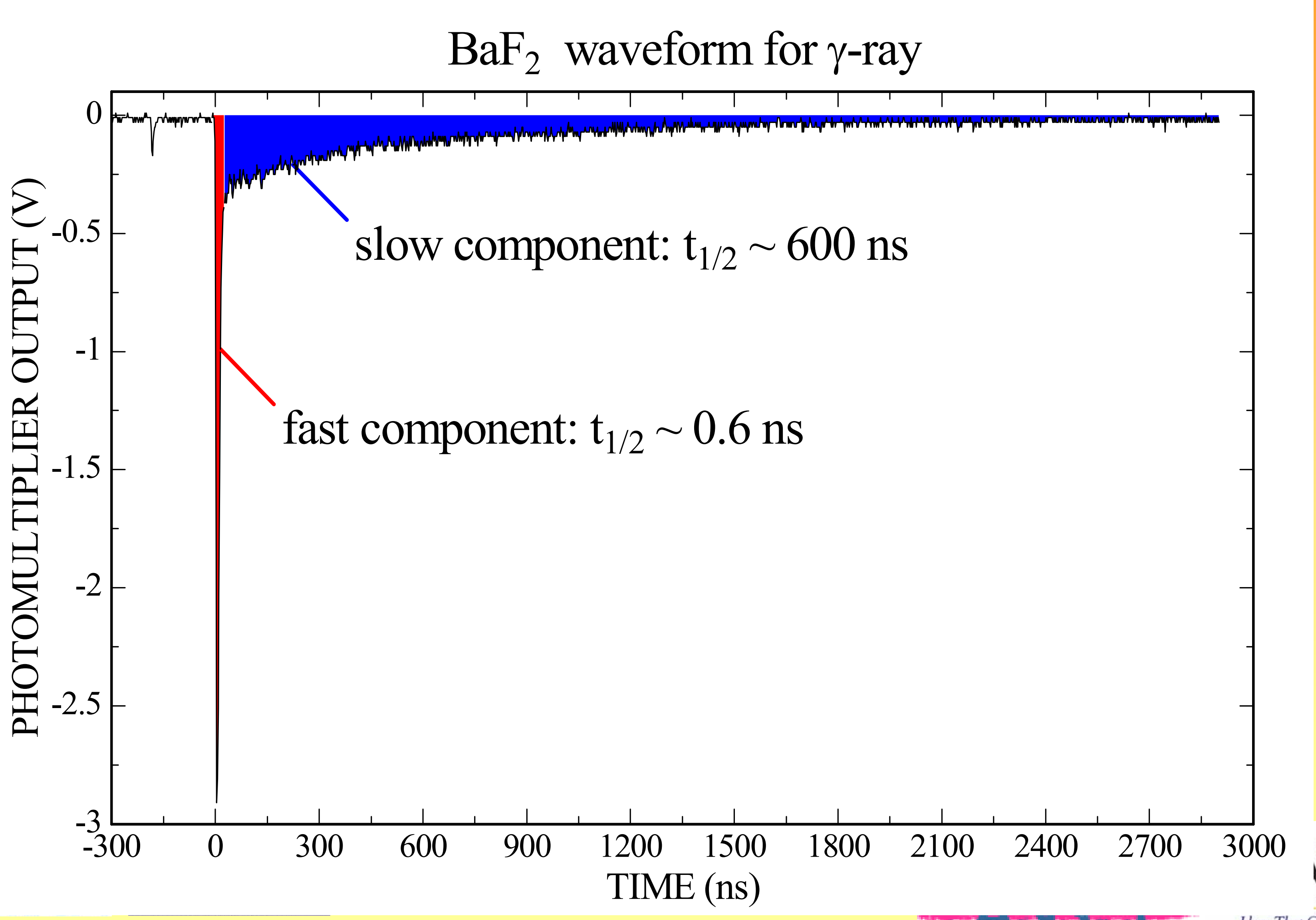
TOF



BaF_2 waveforms - linear

TOF



DAQ – challenges

TOF

	fast component	slow component
Timing	0.6 ns	600 ns
Energy	10 %	90 %
Amplitude	90 %	10 %

- fast component needed for timing & particle identification
- slow component needed for energy resolution

Requirements to DAQ:

- **fast (~ 1 ns)**
- **dynamic range (~ 12 bit)**
- **process data within 50 ms (accelerator)**
- **160 channels**

DAQ – solution

12 channels high gain
12 channels low gain
→ **Acquiris-Crate**

- 14 crates
- 500 MHz PIII
- 500 MS / s
- running MIDAS frontend
- 8 bit / channel
- 2 channel / crystal
- 128000 samples memory

12 channels high gain
12 channels low gain
→ **Acquiris-Crate**

→ **2x2 GHz PC**

- running MIDAS experiment server
- ROOT interface
- 2.4 TB data storage

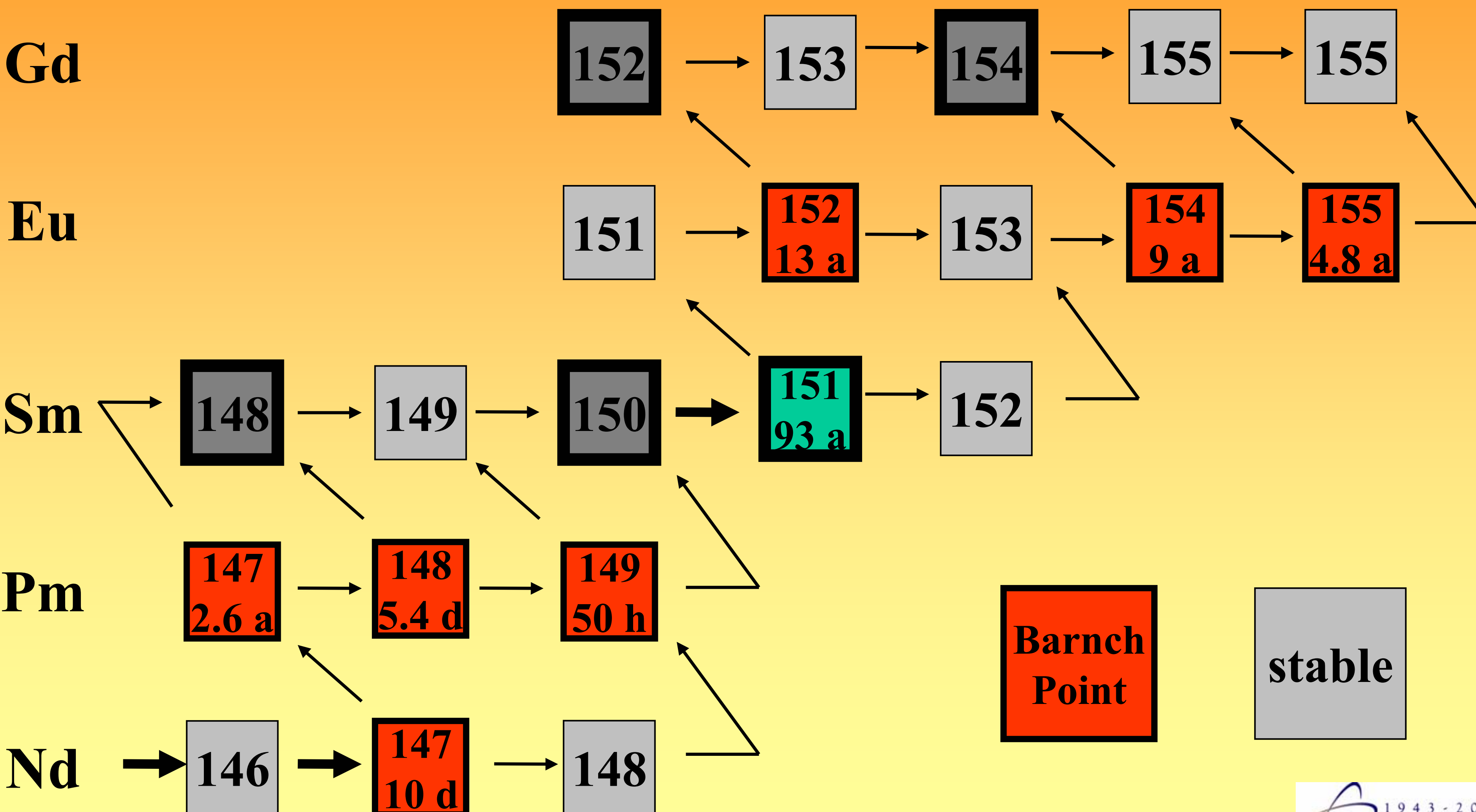
Total:
184 channels for fast comp.
184 channels for slow comp

DAQ - works

First experiments with full array done!

- 320 channels FADC (160 crystals)
- 500 MS/s
- data storage on regular HD
- total file size < 2GB (OS limitation)
- event builder works!!
- problems with synchronization between crates (corrected offline)

Problem with ^{151}Sm



TOF

The early conclusion

"Obviously, none of the existing data sets does result in satisfactory solutions, a dilemma that underlines the importance of the cross sections for the unstable branch point nuclei

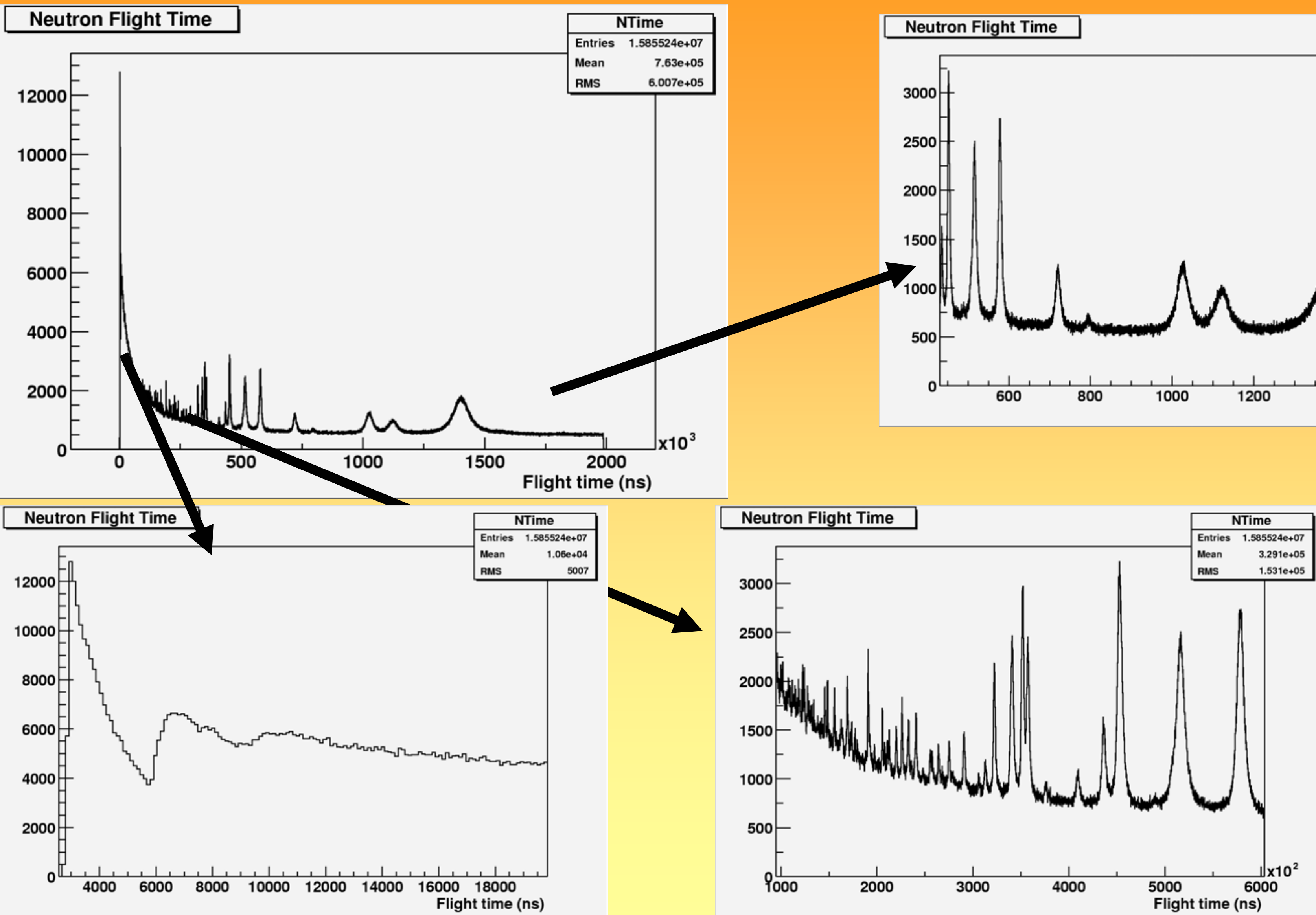
^{147}Pm, ^{148}Pm, and ^{151}Sm.

Therefore, vigorous efforts are necessary towards direct measurements on these radioactive isotopes."

Best et. al. PRC 64, 015801, 2001

0.5 mg of $^{151}Sm(n,\gamma)$ – TOF

TOF



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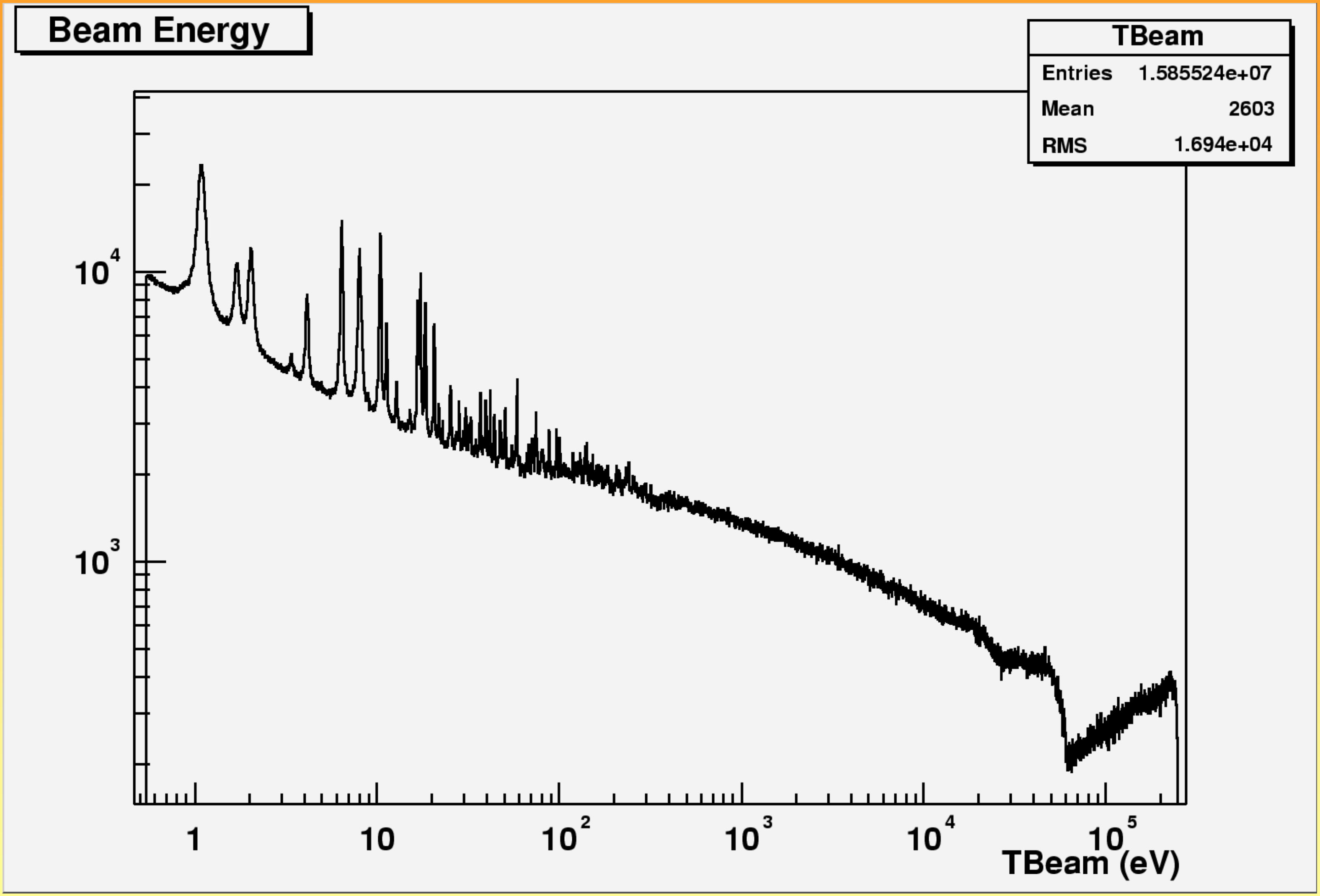
0.5 mg of $^{151}Sm(n,\gamma) - E_n$

TOF



Program

Outlook

Isotope production at ILL, 2002			
Target	Product	Mass	Half life
^{146}Nd	^{147}Pm	3.8 mg	2.6 yr
^{154}Sm	^{155}Eu	8.9 mg	4.8 yr
^{170}Er	^{171}Tm	9.4 mg	1.9 yr

s-process Branch Points, $t_{1/2}$ > 1 yr
^{151}Sm, ^{147}Pm (FY2003)
^{63}Ni, ^{79}Se, ^{81,85}Kr, ^{93}Zr, ^{99}Tc, ^{134}Cs, ^{135}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{163}Ho, ^{171}Tm, ^{176}Lu, ^{179}Ta, ^{185}W, ^{186}Re, ^{193}Pt, ^{204}Tl, ^{205}Pb

s-branch Point	before DANCE	with DANCE
^{63}Ni	-	✓
^{79}Se	-	✓
^{81,85}Kr	-	✓
^{134,135}Cs	-,~	✓
^{147}Nd	-	-
^{147,148}Pm	~,-	✓,-
^{151}Sm	✓	✓
^{153}Gd	-	-,✓
^{154,155}Eu	-,~	✓
^{160}Tb	-	✓
^{163}Ho	-	✓
^{170,171}Tm	-,✓	✓
^{179}Ta	-	✓
^{185}W	-	✓
^{204}Tl	-	✓

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Outlook

What else?

radioactive ion-beams – 1: surrogate reaction

$$^{A}X(n,\gamma)^{A+1}X \sim {}^{A}X(d,p)^{A+1}X$$

inverse kinematics

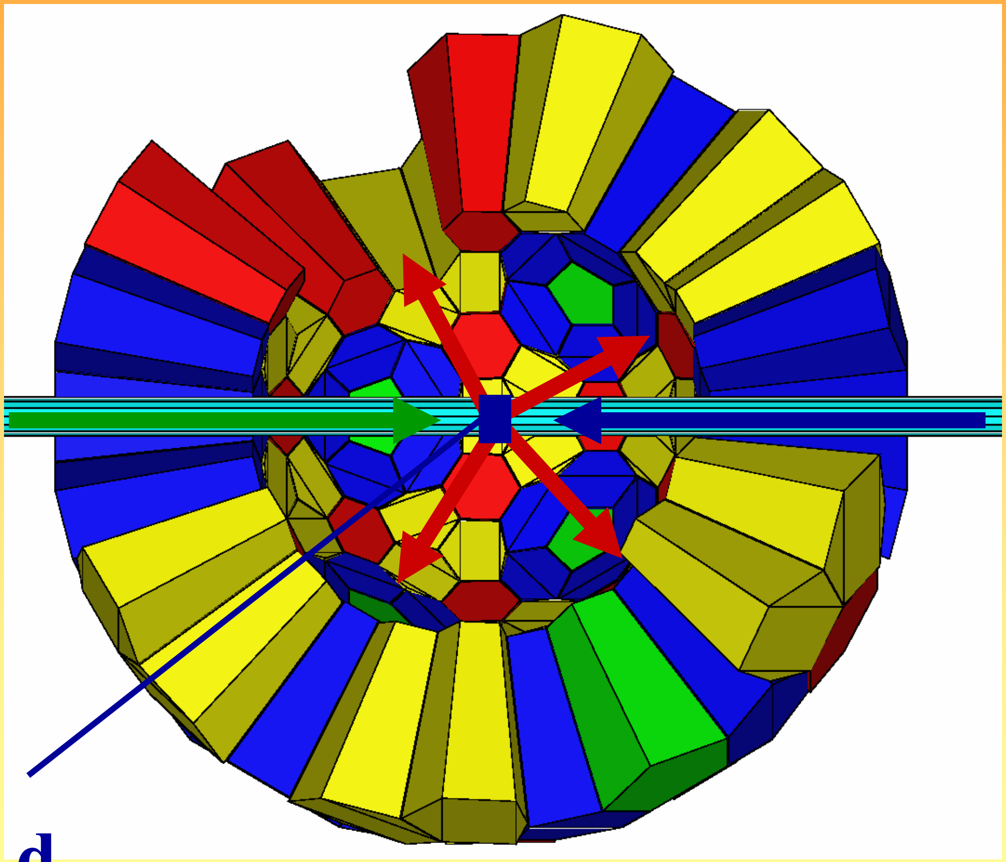
↓

$$\mathbf{d(^{A}X,\ ^{A+1}X)p}$$

needs to be tested and very well understood

What's next?

radioactive ion-beams - 2



sample
$t_{1/2} \sim 10$ d
$m \sim 10\ \mu g$

RIA:

- **spallation source**
- **> 10^{10} particles / s**
- **10 d**

neutrons:

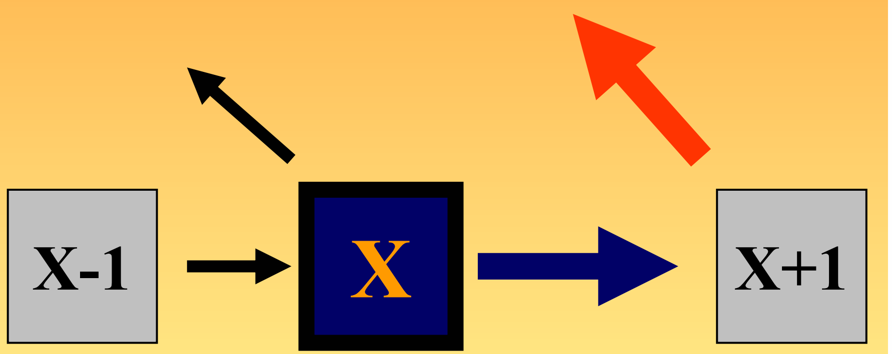
- **VdG**
- **1 .. 500 keV**
- **20 d**

γ-Detector:

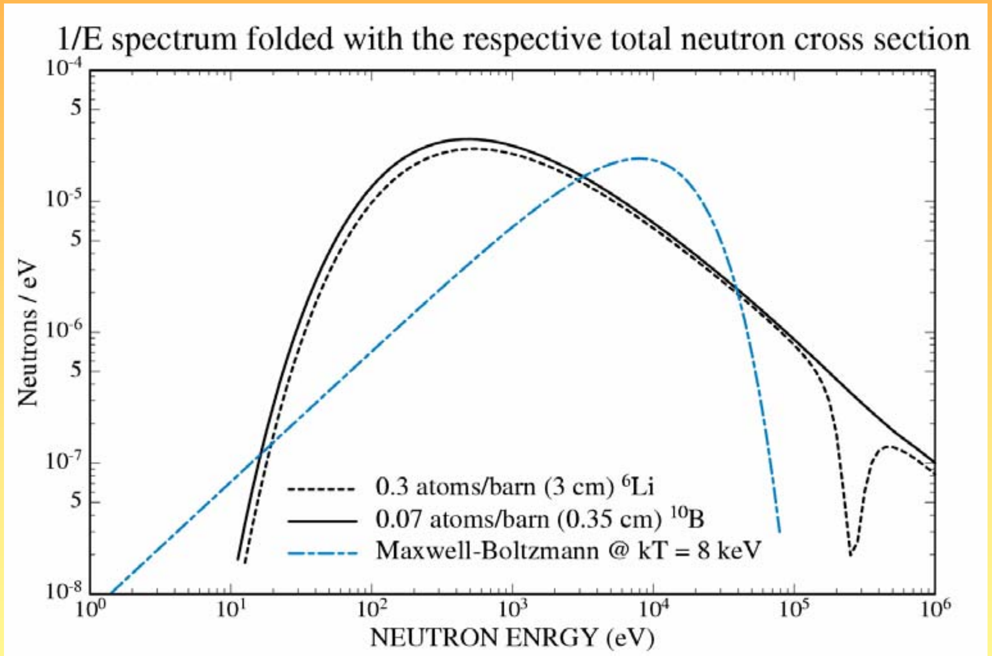
- **4π**
- **ε ≈ 100 %**

What's next?

"advanced activation" close to spallation targets



$t_{1/2} \sim 1$ d



Neutron spectrum needs to be "shaped"

Thanks to:

A. Alpizar, T.A. Bredeweg, J.C. Browne, E.I. Esch, M.M. Fowler, U. Greife, R.C. Haight, R. Hatarik, M. Heil, J.M. O'Donnell, F. Kaeppeler, A. Kronenberg, R.S. Rundberg, J.L. Ullmann, D.J. Vieira, J.B. Wilhelmy, J.M. Wouters